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Interruptible Power Estimation and Auxiliary Service Allocation Using Contract Theory and Dynamic Game for Demand Response in Aggregator Business Model

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ABSTRACT The traditional power market only considers the cost for electricity users, the willingness-to-pay, and the priority of electricity consumption. From the perspective of the electricity industry, only stable power supply, generator equipment set expansion, new power plant construction, and the strengthening of the transmission grid can meet the requirements of electricity users. In recent years, the distributed generation (DG) and energy storage system capacity in microgrid have gradually increased, effectively reducing and suppressing the demand from traditional power sources. In addition, incentive or contractual strategies, such as time-of-use and real-time pricing, can also encourage electricity users to change their electricity consumption behaviors. If the DGs can be integrated into generation aggregators in cooperation with demand response (DR) and efficient load direct/indirect) controls, it can meet the users' demands in auxiliary service (AS) market, as well as achieve a win-win mode for the electricity industry and electricity users. Hence, this study proposes the contract theory (CT) to estimate the interruptible power of the user group (DR aggregator) for DR during peak periods. Then, according to the user group's DR, the dynamic game model (DGM) is used to effectively allocate AS power under the consideration of the DG resource risk situation. In the aggregator business market, experimental results will show that the proposed methods can suppress the use of traditional power sources, effectively activate the proportion of schedulable DG, increase system flexibility, and increase billing charges.

INDEX TERMS Distributed generation (DG), demand response (DR), contract theory (CT), dynamic game model (DGM), interruptible power, auxiliary service (AS).

I. INTRODUCTION

In recent years, Taiwan's electricity load has continued to rise and repeatedly set new high records during the summer season. Operating reserve (OR) is also hitting a record low for the past decade (only 1.64% remaining), resulting in the start of high-cost, inefficient generators. When OR is less than 6% (<0.90 GW), the red light of the power rationing warning is displayed. If it continues to fall below 0.50 GW, the black light of limited power will be displayed and outcomes such as industrial power limitation or rotational load shedding must be activated. Hence, all countries in the world have adopted DR strategies to suppress loads during peak and partial peak periods, to set the demand management schemes for different electricity price structures according to efficiency of usage, time period, season, and interruptible power [1]–[2]. In an electricity liberalized market, if we can cooperate with the advanced metering infrastructure (AMI), the smart meter can be detected and controlled at the load end, and an optimal DR strategy can be implemented to suppress the peak power consumption or generator sets (fuel- or gas-powered units) with high fuel costs. In addition, due to the wholesale market

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TABLE 1. The DR strategies and fluctuating price deduction (Reliable Mode).

DR for Different Timing Notification	Based Price Deduction ($/kW)	Fluctuating Price Deduction Option ($/kW)	Fluctuating Price Deduction Option ($/kW)
15-min-ahead	40	10	Deduction Rate Estimation based on Contract Theory (CT)
30-min-ahead	40	10	
1-h-ahead	40	8	
2-h-ahead	40	6	
Day-ahead	40	4	

Note: deduction equation–reliable mode for DR strategy in Taiwwan
(1) based price deduction: suppressed contract capacity × 40$/kW × 120%
(2) fluctuating price deduction: actual suppressed capacity × suppressed hours × suppressed power price

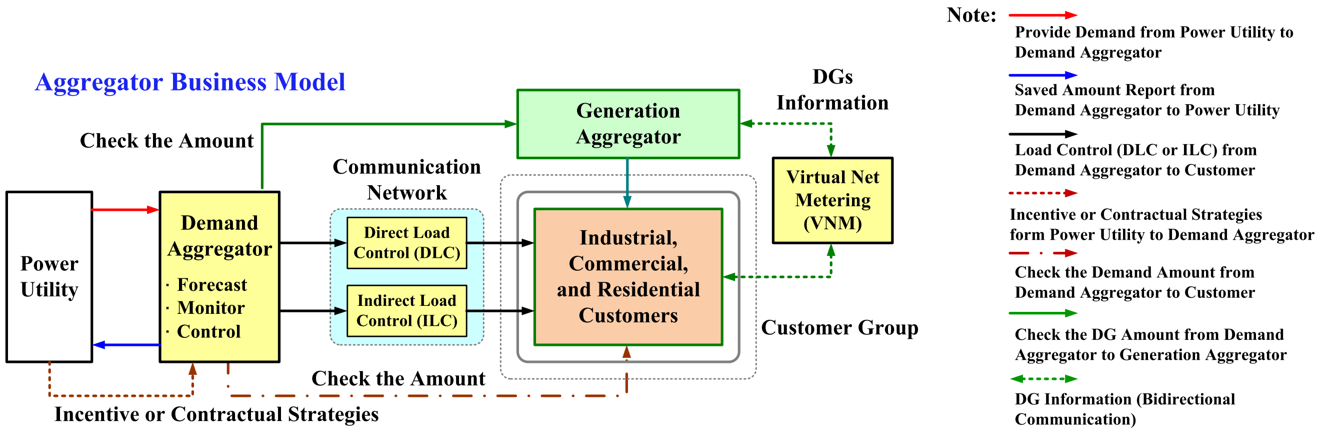

FIGURE 1. Aggregator (demand and generation aggregators) business model in smart grids.

competition, user demand participation can also completely reflect reasonable electricity prices, which can suppress electricity prices and relieve periodical or regional transmission line congestion (reduce line power loss), thus providing a mechanism to maintain power system's safety. The DR mechanism has been proven to effectively change a user's electricity consumption behaviors and moderately reduce the demand for power during peak periods.

Due to the internet-based communication and AMI in the smart grid environment [3], [4], electricity users, including individual large groups of users and individual ones, can use their smart meters to control their personal electricity consumption. Hence, the price and electricity availability can be known through the networked information system [5], [6]. Furthermore, the time-of-use, real-time pricing, critical-peak pricing, and peak-hour feedback price, are provided in response to DR using a price-based pricing strategy to set the electricity price or incentive payment, which can effectively change user behaviors and usage time, whose purpose is to reduce the electricity consumption in the peak period [5]–[7]. When devising the DR strategy, the "direct load control (DLC)" or "indirect load control (ILC)" mode can be implemented to cut off the user's unimportant or controllable loads by using the incentive or contractual strategies [2], [8]–[12], as seen in Figure 1. In addition, the power company can check the users' immediate power consumption through a monitoring center. For an incentive strategy such as electricity price discount or reduction, as seen in Table 1, the electricity user can schedule the continuity or intermittent load, which can reduce peak power consumption or change peak periods, as the so-called ILC mode. The DR strategy can reduce the use of generators with high fuel cost during peak hours. In addition, via collecting data records of smart meters, the electricity industry can analyze the users' usage behaviors and select the suitable DR strategies, decentralize power distribution, and implement green energy development policies.

To reduce the transaction costs of performing DR between the electricity industry and the user groups, past literatures [2], [5]–[8], [13], [14] have pioneered the aggregator business model in liberalized power markets (United States, 2,000 years, as seen in Figure 1. Aggregators can be divided into two roles namely, demand and generation aggregators [15], [16]. In an aggregator business model, aggregators can combine a group of customers into a single electricity purchasing unit and pool DG resources, resulting in the reduction of the expensive power generation and transmission costs from the main grid [16], [17]. A demand aggregator can be a for-profit or non-profit organization, such as a representative of the public user group or private user group. Hence, a large number of small users can be united in a strategic alliance manner to become a "virtual customer," including residential users, business district users, and small and medium industrial users. A demand aggregator can negotiate preferential tariffs with the electricity companies through group or bulk purchases. Individual users who participate have the right to choose "participation" or "exit" in each DR strategy, such as the one-hour-ahead or the two-hour ahead strategies. After deciding on the purchase plan and bidding, the dispatch center and scheduling coordinator will provide the transmission and distribution services. In recent years, the role of generation aggregator is also added in this business model to form a "virtual power plant (VPP)" [16], [18]–[20], which can perform the AS and monitor the availability of DGs in the user group at any time. It can also provide information to demand aggregators using the virtual net metering (VNM) network, as well as distribute and schedule electricity use for participating users, such that excess power can be sold to the electricity industry or another demand aggregator. Thus, aggregator business model integrates demand and generation aggregators, as seen in Figure 1, to implement the DR and AS strategies. Under this business model, individual electricity users can select and join any demand aggregator. Its advantages include users having multiple power purchase options, which stimulates the electricity industry to propose an incentive strategy to the user, that can reduce the demand and line loss during peak periods for high- priced electricity from the main grid [3].

In the traditional power market, while performing the DR, electricity operators use the DLC mode to cut off the users' loads during peak periods. Its scheme lacks interruptible power estimation and DG resource dispatch. Based on the above aggregator business scheme, contract theory (CT) [21], [22] is carried out using novelty formulas to estimate interruptible power with rewards. The process considers the users' demands, electricity purchased cost, DG available capacity, and risk evaluation (uncertain renewable energy [15]) to determine the appropriate interruptible power along with the price or incentive payment [11], [23], leading to both electricity industry and user groups can get profits and rewards. Each demand aggregator can cooperate with multiple generation aggregators and use the dynamic game model (DGM) [14], [24]–[28] to evenly distribute the DG resources, such as renewable energy capacity, AC power generation capacity, and energy storage system capacity, all of which are based on user participation intention, interruptible power, user demand, and decentralized power supply risk factors. In this study, according to the one-hour-ahead strategy and DG information, we will consider the virtual customer across three user groups as a case study to verify the feasibility of the proposed methods for DR and AS tasks. The remainder of this article is organized as follows: Section II describes the Methodology, including the DR and AS Strategies, interruptible power estimation with the CT, and DG distribution with the DGM. Sections III and IV present the Experimental Results, Discussion, and Conclusion, as selecting the day-ahead strategy and the one-hour-ahead strategy to validate the feasibility of the proposed methods.

II. METHODOLOGY

A. DR AND AS STRATEGIES

In the aggregator business market, electricity customers no longer have a single role as electricity users, they can have multiple roles including power purchase, agent purchase, power supply, and so on, which have actively promoted the DG development and technology advancement in European and American countries. The virtual customer composed of user groups has the dual role of consumers and power producers. In this new electricity market model, public/private aggregators and electricity industry form a strategic alliance to perform the DR and AS tasks [20]. In addition, it is also necessary to cooperate with public construction and incentive strategies, as follows:

- Public construction: promote the DGs expansion and deployment, energy storage systems construction, and internet building, and encourage public utility investment, such as a small decentralized power generation and energy storage system at the customer end, for example, the US and German governments have invested in VPP to expand their spare power capacity as much as possible [29].
- Incentive strategy: the price is set according to the time of use, allowing a preferential price offering to temporarily interrupt or adjust the user's partial electricity consumption. For example, as seen in Table 1, the electricity tariff deduction standard for DR is used to suppress the peak load during peak or partial peak periods. Users can then reduce the load according to the DR contract. While executed by the demand aggregator, the interruptible power of the participating users will be performed with the DLC or ILC. If the suppressed load is achieved each time, the rewards are distributed, according to the contract. For example, the US Pacific Power and Gas Company (PG&E) must have a minimum of 75% of the agreed load capacity; otherwise, a fine will be applied if it is less than 50% [30], [31].

To achieve the balance between supply and demand, the AS must provide sufficient spare capacity, load control, frequency control, and voltage control to immediately meet the operating conditions [14]. With the premise of saving energy and reducing carbon emissions, each dispatch is preferentially provided with renewable energy (wind and solar) and energy storage, and then excess renewable energy is resold to the electricity industry or near generation aggregators. If there is insufficient renewable energy (because of weather-related factors), it can use AC power generator (micro turbines) to provide the reserve power. Hence, this study proposes that CT [21], [22] and DGM [24]–[28] can be used to estimate the interruptible power and evenly distribute the DG resources, which enables the implementation of DR and AS operating procedures.

B. INTERRUPTIBLE POWER ESTIMATION WITH CT

Before performing DR, the demand aggregator can monitor the DG capacity at any time via the VNM network [18], [19]. When the user group agrees to participate in current DR strategy, the demand aggregator performs the DR and delivers the scheduling messages to the generation aggregator, which provides the service of the AS to complement the power that

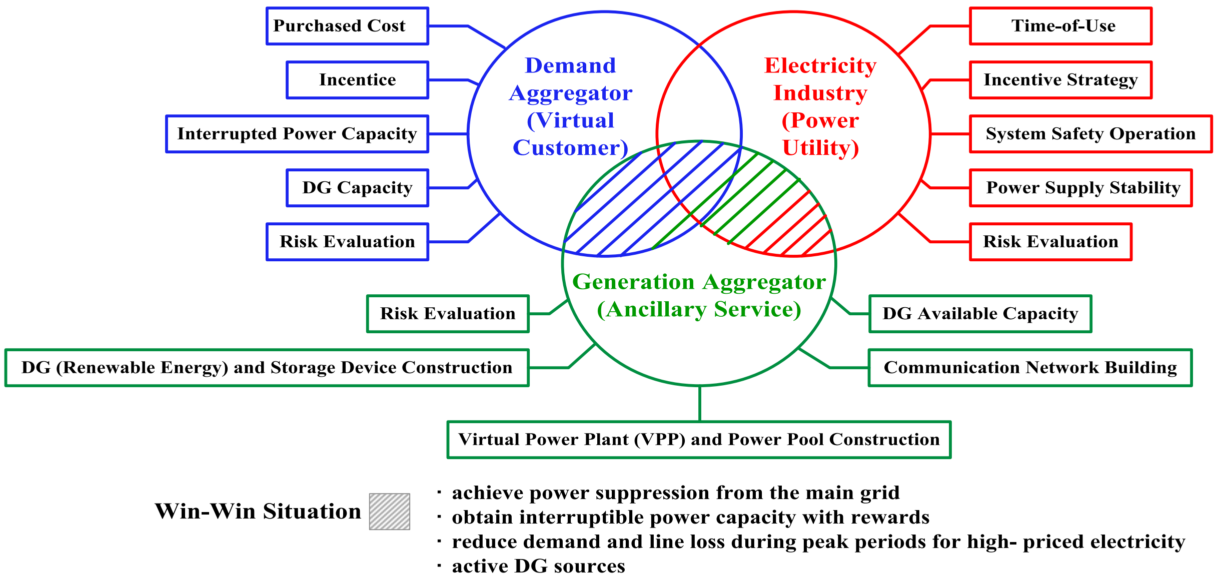

FIGURE 2. Win-win mode of power utility and aggregators (demand and generation).

can be interrupted. As seen in Figure 2, the demand aggregator must be able to obtain benefits, such as (1) electricity purchased cost, (2) interrupted power capacity by the user group, (3) incentive for the power that can be interrupted, (4) DG capacity; and (5) risk evaluation, and for the electricity industry, it has (1) pricing strategy (time-of-use and cumulative electricity price), (2) payment according to electricity price or incentive, suppressing users' demand during peak or partial peak period, (3) power supply stability assessment, (4) system safety operation assessment, and (5) risk evaluation. Thus, considering the users' demands, electricity purchased cost, DG available capacity, and risk evaluation, CT method [21], [22] is derived the novelty formulas to estimate the interruptible power capacity with rewards, as

- **Electricity purchase cost, U_E:**

$$U_E = E(p) - E_{int} = a \times p - E_{int} \tag{1}$$

where "p" is the electricity consumption and the parameter, "a", is the electricity price per kWh (TWD/ kWh). The electricity industry adopts the price measurement strategy, thus, the higher the cumulative electricity consumption, the higher the electricity price. The price can be divided into summer month (from June 1 to September 30) and non-summer month electricity price; and E_{int} represents the cost savings of interruptible power that can be reserved for the user group.

- **Cost savings of interruptible power, U_{int}:**

$$\begin{aligned} U_{int} &= -E_{int}(p) + E_{int} \pm \frac{1}{2} Var_{DG} \\ \Rightarrow \quad U_{int} &= E_{int,\max} - b \times p + E_{int} \pm \frac{1}{2} Var_{DG} \end{aligned} \tag{2}$$

$$E_{int,\max} < 0.5 \times U_{E,\max} \tag{3}$$

The constraint condition is $b > a$, where b is the reward price (TWD/degree) of the interruptible power; $E_{int,max}$ is the maximum interruptible power cost saving, and this parameter is determined by the incentive strategy set by the electricity industry. The participation user demand can usually be lowered by 10%–20%. When the DG capacity is sufficient, the target of 50% demand reduction can be achieved [30], [31], and the $E_{int,max}$ setting conditions are as those in equation (3). When the constraint condition is $b > a$, which means that the reward price b is greater than the electricity price a, it can attract the user group to participate in the DR strategy; $U_{E,max}$ is the maximum purchase cost in a day; Var_{DG} is the DG purchase cost, where $+Var_{DG}$ is the increase of the capacity of the DG, and the excess power can be sold to the electricity industry or other user groups. The increase in capacity increases the profit; $-Var_{DG}$ indicates that the DG can utilize the capacity reduction, which will result in a reward for the power to be interrupted. Adding equations (1) and (2), one can get the comprehensive cost $U = U_E + U_{int}$:

$$\begin{aligned} U &= E(p) - E_{int}(p) \pm \frac{1}{2} Var_{DG} \\ \Rightarrow \quad U &= E_{int,\max} + a \times p - b \times p \pm \frac{1}{2} Var_{DG} \end{aligned} \tag{4}$$

Solving the intersection points of equations (1) and (4), (2) and (4), as shown in Figure 3(a), the range of interruptible power can be estimated as follows:

$$\begin{cases} U = a \times p - E_{int} \\ U = E_{int,\max} + a \times p - b \times p \pm \frac{1}{2} Var_{DG} \end{cases}$$
$$\Rightarrow p_{\max} = \frac{E_{int,\max} + E_{int} \pm Var_{DG}}{b} \tag{5}$$

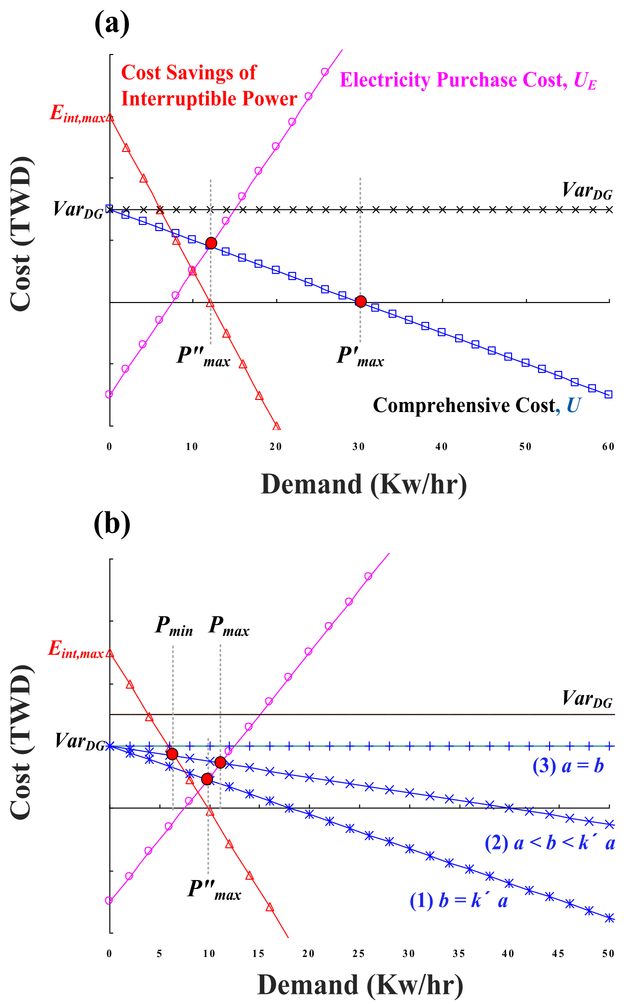

FIGURE 3. Interruptible power estimation based on CT method.

$$\begin{cases} U = E_{int,\max} - b \times p \pm \frac{1}{2} Var_{DG} \\ U = E_{int,\max} + a \times p - b \times p \pm \dfrac{1}{2} Var_{DG} \end{cases}$$
$$\Rightarrow p_{\min} = \frac{E_{int}}{a} \tag{6}$$

When the user group performs the DR, the aggregator can temporarily interrupt or adjust the user's partial power within the range of $p_{min} < p < p_{max}$. As shown in Figure 3(a), it can reduce the high electricity price from the main grid during the peak or partial peak period. If the immediate DR is performed, with 1 h as reference, timing slot, $h = 1, 2, 3, \ldots, 24$, the interruptible power that can be estimated at time h is as follows:

$$S_{int,h} = [p_{\min,h}, p_{\max,h}] \tag{7}$$

The demand aggregator can determine the interruptible power based on the purchasing electricity cost, the cost saving of interruptible power, and the DG capacity. In this range, the user group can get the reward. Hence, the electricity industry can get the profit of its electricity sales. If only considering the comprehensive cost U, the range of maximum interruptible power can be estimated using equation (4):

$$U = E_{int,\max} + a \times p - b \times p \pm \frac{1}{2} Var_{DG} = 0$$
$$\Rightarrow \quad p'_{\max} = \frac{E_{int,\max} \pm \frac{1}{2} Var_{DG}}{b - a}, \tag{8}$$

The constraint condition is: $a \neq b$. Then, the maximum interruptible power, p_{max}, is estimated using equation (8), as shown in Fig. 3(a). Both the electricity industry and the user group cannot obtain the maximum benefit. This study is based on the incentive basis, the constraint condition is "$b > a$", and the adjustment parameter is k, $k > 1$. If considering the comprehensive benefit of the maximum benefit [22], then the equation (4) can be modified to equation (9):

$$U' = kE(p) - E_{int}(p) \pm \frac{1}{2} k^2 Var_{DG} \tag{9}$$

The parameter k is an adjustable parameter, and $k^2 Var_{DG}$ is set to facilitate the differential operation. The differential is as per equation (9) and is set to zero ($U' = 0$) to obtain the maximum value:

$$\frac{\partial U'}{\partial k} = a \times p \pm k \times Var_{DG} = 0 \tag{10}$$

Then, it can solve the optimal interruptible power reward Price, b_{opt}, and adjust the parameter k, as

$$k = ap/Var_{DG} \tag{11}$$
$$b_{opt} = k \times a \tag{12}$$

If we substitute equation (12) into equation (5), the maximum interruptible power, p_{max}, can be modified as follows:

$$p''_{\max} = \frac{E_{int,\max} + E_{int} - Var_{DG}}{b_{opt}} = \frac{E_{int,\max} + E_{int} - Var_{DG}}{k \times a} \tag{13}$$

Then, if we consider the best interests of both parties, the maximum interruptible power is p_{max}. From the perspective of electricity industry, adjusting the parameter $b = k \times a$ can provide an incentive strategy, and the range of maximum interruptible power and the price of the interruptible power per incentive conditions are as follows:

$$a < b < b_{opt} \Rightarrow a < b < k \times a \tag{14}$$

The interruptible power price per kWh (TWD/kWh) can be set in the range of Equation (14). If the parameter b is formulated, the maximum interruptible power can be estimated by Equation (5). The critical value of p''_{max}, and its range is as follows:

$$S_{\text{int},h} = \begin{cases} [P_{\min}, P''_{\max}] \\ [P''_{\max}, P_{\max}] \end{cases} \tag{15}$$

As seen in Fig. 3(b), the development of different interruptible power reward strategies will result in a comprehensive cost of (1)–(3). With the range of interruptible power from

Equation (15), the electricity industry can consider the power supply stability, DG available capacity, and risk evaluation to select the appropriate range of interruptible power along with the price or incentive payment. Within this range, both the electricity industry and the user groups can get profits, translating into a win-win situation.

C. DG DISTRIBUTION WITH THE DGM

At the user end, demand aggregators consider the demand for participating user groups and estimate the range of interruptible power. In this range, rewards can be obtained, and this bonus can be applied to "purchase DG" or "public equipment maintenance." The interruptible power is allocated according to the user's demands and the available DG resources are used to supplement the capacity of the user group. If the renewable energy capacity is sufficient, the renewable energy is given priority the demand aggregators can simultaneously perform AS task and cooperate with more than two generation aggregators. The purchase, assisted by the a generation aggregator, has its obligation to make up for the interruptible power. For the notification time, such as 15-min-ahead, 30-min-ahead, 1-h-ahead, 2-h-ahead, and day-ahead strategies, the demand aggregator can perform DR and AS, and each user can reduce their power consumption according to the incentive strategy.

Under the immediate DR strategy, after the aggregator purchases electricity, it can determine the purchase price (announcement price) and DR capacity, with 1-h-ahead strategy, where $h = 1, 2, 3, \ldots, 24$. At this time, the required capacity $S_{DG,h}$ can be obtained at time h for the DG, as seen in Equation (16):

$$S_{DG,h} = (\sum_{l=1}^{Nl} S_{pl,h}) - (\sum_{l=1}^{Nl} S_{l,h}) = S_{int,h} \tag{16}$$

where $S_{pl,h}$ is the original demand (kW) of each participating user; $S_{l,h}$ is the demand (kW) determined by each participating user, according to the announcement price and the interruptible power reward; $S_{int,h}$ is the willingness of the user group to reduce the interruptible power load; and $l = 1, 2, 3, \ldots, Nl$, represents the number of participating users in the user group. The interruptible power can be estimated using Equations (11)–(14). The demand aggregator can use the DG capacity to determine the interruptible power by each user, $S_{\mathrm{int},h}$ (assigned according to proportion):

$$S_{l,\mathrm{int},h} = (S_{int,h} \times S_{l,h})/(\sum_{l=1}^{Nl} S_{l,h}) \tag{17}$$

$$p_{\min} \leq \sum_{l=1}^{Nl} S_{l,\mathrm{int},h} \leq p_{\max} \tag{18}$$

When the aggregator determines the amount of electricity purchased during period h, the ownership grade of each user is estimated by equation (19), as seen in Fig. 4(a):

$$DR_{l,h} = \exp[-1 \times (\frac{1 - S_{l,h}/S_{pl,h}}{0.5})^2] \tag{19}$$

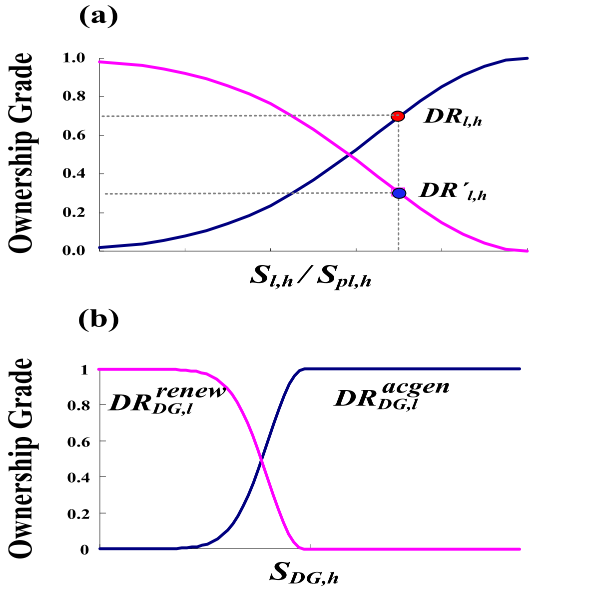

FIGURE 4. Ownership function. (a) Ownership of participation in the DR, (b) User's ownership to DG resource demand.

$$DR'_{l,h} = (1 - DR_{l,h}) \tag{20}$$

where $DR_{1,h} \in [0, 1]$ is the grade of the user's DR during the period h, represented by an ownership grade of 0 to 1. When it approaches to 1, it indicates that the user has high willingness to participate. The higher the willingness to DR, the higher the willingness to return to the original demand after the interruptible power distribution. If the user does not intend to return to the original demand after the interruptible power distribution or is unwilling to participate, then the ownership grade in will be lower (equal to 0 or approach to 0). Conversely, equation (20) will increase or be closer to 1. Note that Equation (20) is complementary to equation (19), as shown in Fig. 4(a).

The user's demand for DG resources, as shown in Fig. 4(b), includes the renewable energy S_{renew} and the alternative energy S_{acgen}. Because of the uncertainty of renewable energy for the generation aggregators, renewable energy has the risk of instability. This study focuses on the variation of renewable energy "$\pm Var_{DG}$" to consider DG resource allocation:

$$S_{DG,h} = \sum_{l=1}^{Nl} S_{l,\mathrm{int},h} \tag{21}$$

$$DR_{DG,l}^{renew} = \begin{cases} 1, & 0 \leq S_{DG,h} \leq \Delta_1 \\ \exp(\frac{-1}{2} \times (\frac{S_{DG,h} - \Delta_1}{S_{renew}/Nl})^2), & S_{DG,h} > \Delta_1 \end{cases} \tag{22}$$

$$DR_{DG,l}^{acgen} = \begin{cases} \exp(\frac{-1}{2} \times (\frac{S_{DG,h} - \Delta_2}{S_{acgen}/Nl})^2), & 0 \leq S_{DG,h} \leq \Delta_2 \\ 1, & S_{DG,h} \geq \Delta_2 \end{cases} \tag{23}$$

$$\Delta_1 = S_{renew} \pm \frac{Var_{DG}}{K}, \quad \Delta_2 = S_{acgen} \mp \frac{Var_{DG}}{K} \tag{24}$$

TABLE 2. Dynamic game model strategy.

	Customer# / DG#	Consumption in Peak Period (10:00-12:00a.m., 13;00-17:00 p.m.)	
• Renewable Energy • AC Generator • Storage Energy		(1) $DR_{l,h}$	(2) $DR^{'}_{l,h}$
	(3) Renewable Energy	$s_{l1} = DR_{l,h} \times DR_{DG,l}^{renew}$	$s_{l2} = DR^{'}_{l,h} \times DR_{DG,l}^{renew}$
	(4) AC Generator	$s_{l3} = DR_{l,h} \times DR_{DG,l}^{acgen}$	$s_{l4} = DR^{'}_{l,h} \times DR_{DG,l}^{acgen}$
Mixed Operation		$s_{l1} + s_{l3}$	$s_{l1} + s_{l3}$

Among them, Var_{DG} is the purchase cost variation (TWD) of DG, and the parameter "K" is the purchase price (TWD/kW) of renewable energy. When the parameter K decreases, the demand for the alternative power S_{acgen} decreases; however, it increases the demand for S_{acgen}. The DGM allocates the DG capacity based on the user's DR and DG resource requirements. The user's DR can be divided into two strategies [14], [24], [25]: (1) grade of willingness (cooperation) and (2) grade of unwillingness (non-cooperation). The demand for DG resources can be divided into two options: (3) renewable energy and (4) alternative energy. The DGM strategy, as shown in Table 2, can be divided into four combinations including: (1) cooperative, renewable energy; (2) non-cooperative, renewable energy; (3) cooperative, AC Generator; and (4) non-cooperative, AC Generator. The representation of the four combinations is as follows [1], [14], [27]:

$$S_l = \begin{bmatrix} DR_{l,h} \times DR_{DG,l}^{renew} & DR'_{l,h} \times DR_{DG,l}^{renew} \\ DR_{l,h} \times DR_{DG,l}^{acgen} & DR'_{l,h} \times DR_{DG,l}^{acgen} \end{bmatrix} = \begin{bmatrix} s_{l1} & s_{l2} \\ s_{l3} & s_{l4} \end{bmatrix} \quad (25)$$

If each user uses two DG supplies at the same time, the two combined probability sizes can be added together to prioritize the user groups for the demand, as shown in equation (26):

$$S_l^{+} = \max[(s_{l1} + s_{l3}), (s_{l2} + s_{l4})] \quad (26)$$

The sorting method will adopt a cooperative strategy and a non-cooperative strategy and allocate the available DG resources [1], [18]:

- Renewable Energy Distribution-Cooperative Strategy:

$$S_{l,renew} = S_{l,\text{int},h} \times \left(\frac{s_{l1}}{\sum_{l=1}^{Nl} s_{l1} + s_{l3}}\right) \quad (27)$$

- Renewable Energy Distribution - Non-Cooperative Strategy:

$$S_{l,renew} = S_{l,\text{int},h} \times \left(\frac{s_{l2}}{\sum_{l=1}^{Nl} s_{l2} + s_{l4}}\right) \quad (28)$$

- AC Generator - Cooperative Strategy:

$$S_{l,acgen} = S_{l,\text{int},h} \times \left(\frac{s_{l3}}{\sum_{l=1}^{Nl} s_{l1} + s_{l3}}\right) \quad (29)$$

- AC Generator - Non-Cooperative Strategy:

$$S_{l,acgen} = S_{l,\text{int},h} \times \left(\frac{s_{l4}}{\sum_{l=1}^{Nl} s_{l2} + s_{l4}}\right) \quad (30)$$

the constraint condition:

$$S_{DG,h} = S_{renew,h} + S_{acgen,h} = \left(\sum_{l=1}^{Nl} S_{l,renew}\right) + \left(\sum_{l=1}^{Nl} S_{l,acgen}\right) \quad (31)$$

$$0.25 \times S_{acgen,\max} \le S_{acgen} \le S_{acgen,\max} \quad (32)$$

$$0.50 \times S_{renew,\max} \le S_{storage} \quad (33)$$

Among them, $S_{l,renew}$ allocates capacity for each user's renewable energy capacity, and $S_{l,acgen}$ allocates capacity for AC generator capacity. Equations, (17)–(20), represent DG that can be obtained after the user group adopts the cooperative DR strategy. Equations, (21) – (24), are the combinations of operation condition of the DG. The DG capacity $S_{DG,h}$ must meet at least 20% – 50% of the maximum demand. For the users who adopt non-cooperative DR strategy, they can still participate in DG purchase, but must wait after participating user group distribution.

III. EXPERIMENTAL RESULTS AND DISCUSSION

This study assumes a demand aggregator as a virtual user consisting of 3 residential user groups. At demand side, electricity users formed a group as a single electricity purchasing unit, as evidenced from the daily demand profiles of 3 residential users in Fig. 5(a). The daily demand profile is shown as the peak period (10:00 a.m.–12:00 p.m and 13:00 p.m.–17:00 p.m) and partial peak period (12:00 p.m–13:00 p.m), two timing periods, respectively. The maximum demand, 52.8 kW, occurs at 10:00am, including customer #1: 15.0kW, customer #2: 19.8kW, and customer #3: 18.0kW. The generation aggregator can provide available DG capacity throughout the day, as seen the DG profile in Fig. 5(b), including AC Generator (20 kW), renewable energy (solar and wind), and energy storage system capacity of at least 50% of maximum demand. The DR can reduce the peak period demand using the ILC, as a 20% of demand of interruptible power during peak period, as seen pink solid line in Fig. 5(b). In addition, the demand aggregator also performs DR according to the participating contract. For example,

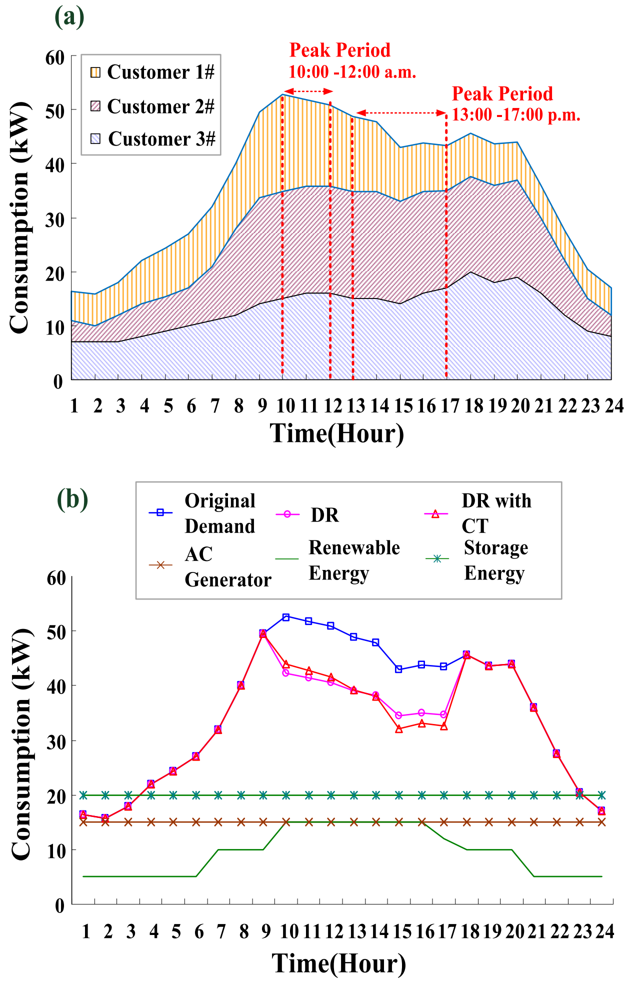

FIGURE 5. Daily demand profile and DG capacity profile. (a) Virtual user daily load curve, (b) Virtual user daily load curve, traditional DR allocation, DR allocation with CT method, and DG capacity (including renewable energy, AC generator, and storage energy).

the execution time can be from June to September (summer month electricity), and the daily notification time can be 30 min, 1 h, 2 h, or day-ahead for DR. According to the different notification timelines, the electricity fee deduction standard is given, as shown in Table 1. This study selected to adopt the "day-ahead" and the "1-h-ahead" strategies to test the feasibility of the proposed strategy, and the results are shown below:

A. DAY-AHEAD STRATEGY: PLAN OF ABOUT 20% OF THE DEMAND OF INTERRUPTIBLE POWER PER TIME PERIOD

Peak period DR and DG resource allocation results are shown in Fig. 6. This study assumes that the DR strategy is implemented in a reliable mode, and the "day-ahead" strategy is adopted to predict the possible demand of the user group on the previous day and to reduce the load with more than 20% each time, according to the contract. At this time, each user reduces power consumption according to incentives, such as ILC, time-controlled switches and group control switches, which can perform periodic operation strategies from 10:00 am. to 5:00 pm for a total of 8 h, as seen, the DR

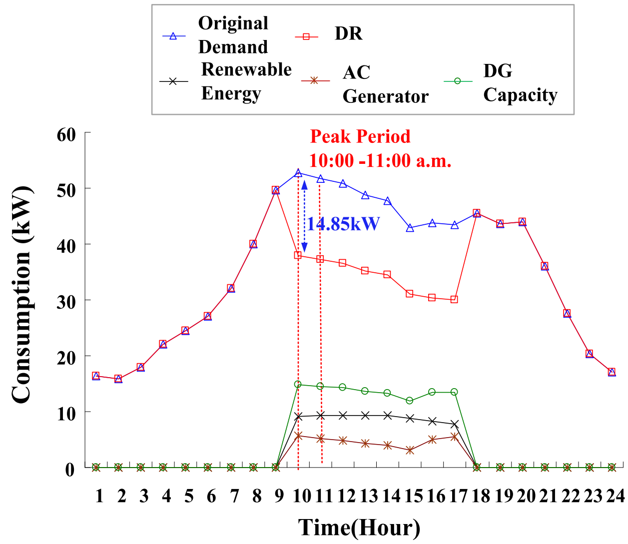

FIGURE 6. Day-ahead notification strategy.

curve (as red solid line) in Fig. 6. For a case study, during the period of 10:00 a.m.-11:00 a.m., the interruptible power capacity is 14.85 kW (maximum demand: 52.8 kW, demand response: 37.95 kW). The demand aggregator only needs to purchase 37.95 kW during the execution period. Thus, the low electricity price can also be purchased from the main grid. In the 8-h DR, the average demand can be suppressed by 13.67 kW (26.89%) per hour with a peak at 10:00 a.m. The 10:00 a.m. - 12:00 p.m time period (peak period) is taken as case studies. The results of DG resource allocation are shown in Table 3. According to the electricity fee deduction standard of Table 1, various DR strategies for different timing notification are performed, and the user group can obtain the electricity fee deduction reward, as seen in Table 4. The basic electricity fee and variable electricity fee deductions were \$712.80 and \$437.77, respectively. Demand aggregator can make a contract with the user group and each time the electricity bill is settled, the reward is also distributed according to the contract or used to purchase the DG capacity subsidy fund. The test can verify the feasibility of the proposed method.

B. ONE-HOUR-AHEAD STRATEGY: USING CT METHOD TO ESTIMATE THE RANGE OF INTERRUPTIBLE POWER

Assume that all three residential users adopt cooperative strategies, all of which are involved in DR and DG resource requirements. During the peak period, the price per kWh is 4.00 TWD/kWh. The demand aggregator can plan a 20% of demand of interruptible power every time. Its DR for peak period planning is shown in Fig. 5(b) as a pink solid line. The relevant parameters between electricity industry and demand aggregators, including the cost of maximum interruptible power savings, $E_{int,max}$ (the electricity industry can tolerate up to about 30% of the maximum demand), the cost-saving E_{int} of the user group to save power, the cost of the DG, Var_{DG}, and the price of electricity per kWh, a (TWD/kWh), as seen in Table 5.

TABLE 3. Peak period (10:00a.m.–12:00p.m.) DG allocation results.

Time	Customer	$DR_{l,h}$	$DR'_{l,h}$	$DR_{DG,l}^{renew}$	$DR_{DG,l}^{acgen}$	Dynamic Game Model (DGM)				Renewable Energy (kW)	AC Generator (kW)
						s_{l1}	s_{l3}	s_{l2}	s_{l4}		
10:00-11:00 a.m.	1#	0.9681	0.0319	0.9231	0.4296	0.8937	0.4159	0.0294	0.0165	3.0709	1.4290
	2#	0.9616	0.0384	1.0000	0.5883	0.9616	0.5657	0.0384	0.0226	3.1165	1.8335
	3#	0.9544	0.0456	0.9500	0.7492	0.9068	0.7150	0.0433	0.0341	3.0192	2.3807
								Total (kW)		9.2066	5.6432
Time	Customer	$DR_{l,h}$	$DR'_{l,h}$	$DR_{DG,l}^{renew}$	$DR_{DG,l}^{acgen}$	Dynamic Game Model (DGM)				Renewable Energy (kW)	AC Generator (kW)
						s_{l1}	s_{l3}	s_{l2}	s_{l4}		
11:00-12:00 a.m.	1#	0.9638	0.0362	0.9873	0.5341	0.9515	0.5148	0.0357	0.0205	3.1149	1.6851
	2#	0.9616	0.0385	1.0000	0.5883	0.9616	0.5657	0.0384	0.0226	3.1165	1.8336
	3#	0.9638	0.0362	1.0000	0.5341	0.9638	0.5147	0.0362	0.0193	3.1289	1.6710
								Total (kW)		9.3603	5.1897

TABLE 4. DR strategy cost deduction results.

DR for Timing Notification		Cost deduction
30-min-ahead	Base price	14.85kW × 40$/kW × 1.2 = 712.80$
	Fluctuating price	13.67kW/hr × 10$/kW × 8hr = 1093.60$
1-h-ahead	Base price	14.85kW × 40$/kW × 1.2 = 712.80$
	Fluctuating price	13.67kW/hr × 8$/kW × 8hr = 874.88$
2-h-ahead	Base price	14.85kW × 40$/kW × 1.2 = 712.80$
	Fluctuating price	13.67kW/hr × 6$/kW × 8hr = 656.16$
Day-ahead	Base price	14.85kW × 40$/kW × 1.2 = 712.80$
	Fluctuating price	13.67kW/hr × 4$/kW × 8hr = 437.44$

TABLE 5. DR allocation result based on CT method: recommended interruptible power, reward, and DG allocation.

Time (Hour)	$E_{int,\,max}$ (TWD)	E_{int} (TWD)	Var_{DG} (TWD)	a (TWD/kWh)	Scheduled Interruptible Power (kW)	k	Reward b (TWD/kWh)	Interruptible Power (kW)	S_{renew} (kW)	S_{acgen} (kW)
10-11	60	20	30	4	10.56	1.41	5.63	8.87	8.87	0.00
11-12	60	20	30	4	10.36	1.38	5.52	9.05	9.05	0.00
12-13	60	20	30	4	10.16	1.35	5.42	9.22	9.22	0.00
13-14	60	20	30	4	9.76	1.30	5.21	9.60	9.60	0.00
14-15	60	20	30	4	9.56	1.27	5.10	9.80	9.80	0.00
15-16	60	20	30	4	8.60	1.15	4.59	10.90	10.90	0.00
16-17	60	20	30	4	8.76	1.17	4.67	10.70	10.70	0.00
17-18	60	20	30	4	8.68	1.16	4.63	10.80	10.80	0.00

If using day-ahead strategy, it predicts the possible demand of the user group on the previous day, and then reduces the demand for each time period by 20% according to the agreed time. From 10:00a.m. to 5:00p.m, a total of 8 h can reduce 76.44 kWh of electricity. This study implements the DR strategy with a timing slot to plan the interruptible power capacity with the CT method, which suggests the optimal interruptible power capacity, as seen in Table 5 and solid red line in Figure 5(b). Considering the peak demand, as case study at 10:00 a.m., it notifies the scheduled suppression of 10.56 kW (about 20%) is implemented at 10:00 a.m. After the CT method is planned, it is recommended that the interruptible power capacity is 8.87 kW (as seen in Table 5), and the reward for interruptible power is 5.63 TWD/kWh, which are about 1.41 times per kWh. During this timing slot, the renewable energy capacity is sufficient to provide the AS, aggregator can, through the VNM network, confirm the available DG capacity, and deliver the scheduling commands to the generation aggregator to provide a DG that can be utilized.

For each user, this study uses a DGM to compute the probability of the four combinations to get the maximum probability as evaluation indicators in Equation (25). If a fully cooperative combination is adopted, it would be as follows:

$$\begin{aligned} Index_{l*} &= \max\{(s_{11}+s_{13}), (s_{21}+s_{23}), (s_{31}+s_{33})\} \\ &= \max\{(0.9493+0.0000), (0.9246+0.6622)\}, \\ &\qquad (0.8150+0.0710)\} \\ &= \max\{0.9493, 1.5868, 0.8860\} \end{aligned}$$

Then, according to the value of index $Index_l*$, the priority order is arranged by the sorting algorithm, which is used to identify the priority order for the DG distribution. The index $Index_l$ evaluates the possible distributed generation

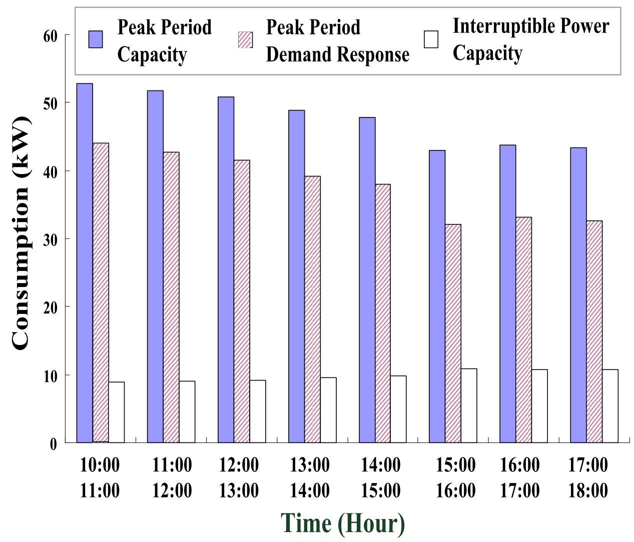

FIGURE 7. DR and interruptible power in 8 peak hours.

type during the contracted timing slot, and the user can choose to participate or exit. When the user chooses to exit, the assigned rights will be transferred to other users. In this case study, the priority of evaluation results are showed as follows:

User 2# = 1.5868 > User 1# = 0.9493 > User 3# = 0.8860, The generation aggregator is applicable to Equations (27)–(33) to allocate the DG to the user group, as shown in Table 6. It performs the operation procedures of "DR" and "AS", as shown in the Appendix.

Similarly, when the peak demand is not the maximum, take 14:00 p.m. in the afternoon as a case study, the original scheduled interruptible power capacity is 9.56 kW (as seen in Table 5), and the CT method suggests that the interruptible power capacity is 9.80 kW. Because of the demand from the main grid during this timing slot, it has been reduced, and the available capacity of the DG is sufficient; hence, the interrupted power capacity is increased by 0.24 kW than the scheduled, and the results of the DG scheduling are shown in Table 6. According to the contract implementation of the DR of eight time periods, the demand for the main grid can be effectively reduced from 10:00 am. To 5:00 p.m (8 hours), which can reduce the power consumption of 78.97 kWh. On an average, the power consumption is suppressed by 9.87 kWh, and the average power consumption of the peak

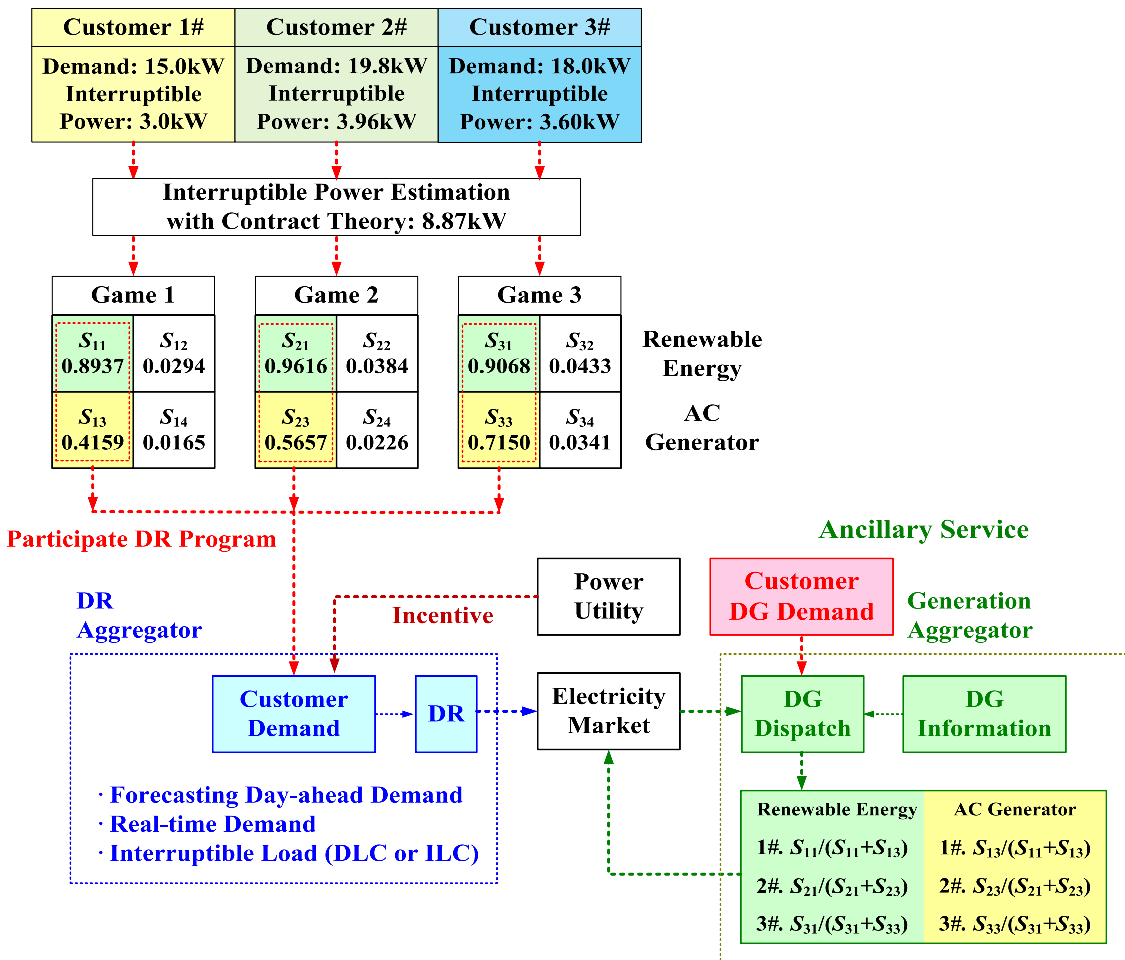

FIGURE 8. DR and AS performing procedures.

TABLE 6. Peak period (10:00a.m.-11:00p.m. and 14:00p.m.-15:00p.m.) DG allocation result.

Time	Customer	$DR_{l,h}$	$DR'_{l,h}$	$DR_{DG,l}^{renew}$	$DR_{DG,l}^{acgen}$	Dynamic Game Model (DGM)				Renewable Energy (kW)	AC Generator (kW)
						s_{l1}	s_{l3}	s_{l2}	s_{l4}		
10:00-11:00 a.m.	1#	0.9681	0.0319	0.9805	0.0000	0.9493	0.0000	0.0312	0.0000	2.46	0.00
	2#	0.9616	0.0384	0.9889	0.6887	0.9246	0.6622	0.0380	0.0265	4.12	0.00
	3#	0.9544	0.046	0.8539	0.8458	0.8150	0.0710	0.0389	0.0386	2.29	0.00
								Total (kW)		8.87	0.00
Time	Customer	$DR_{l,h}$	$DR'_{l,h}$	$DR_{DG,l}^{renew}$	$DR_{DG,l}^{acgen}$	Dynamic Game Model (DGM)				Renewable Energy (kW)	AC Generator (kW)
						s_{l1}	s_{l3}	s_{l2}	s_{l4}		
14:00-15:00 p.m.	1#	0.9681	0.0318	0.9805	0.0000	0.9492	0.0000	0.0312	0.0000	2.81	0.00
	2#	0.9616	0.0384	0.9889	0.6886	0.9245	0.6622	0.0380	0.0264	4.69	0.00
	3#	0.9759	0.0240	0.7798	0.3107	0.7610	0.0156	0.0187	0.0075	2.30	0.00
								Total (kW)		9.80	0.00

period is about 20.91%, as shown in Fig. 7. At the same time, according to the user's demand, the available capacity of the DG, the effective response of the optimal interruptible power capacity, and the incentive to suppress the use of electricity can be shown, which can help to avoid the capacity exceeding the contract in peak hours. In addition, to effectively suppressing the maximum demand during the peak period, it can also reduce the power demand on the main grid and also the cost of expensive fuel during the perk period, transmission and distribution costs, and transmission and distribution losses.

Moreover, the demand aggregator can have contract with the user group. Each time the electricity bill is settled, the reward is distributed, according to the contract or used to purchase the AS and construct the DG and energy storage system equipment. The feasibility of the CT method is verified by the case studies. The DGM allocates the DG capacity to each user according to the demand of the user group and the demand for DG resources. The allocation result is shown in Table 6. Because renewable energy capacity and energy storage system capacity are enough to provide AS, the DG distribution is primarily based on renewable energy, and three users are allocated with 2.46 kW, 4.12 kW, and 2.29 kW respectively. If there is sufficient renewable energy capacity available, the generation aggregator can provide AS to other groups of users or aggregators.

IV. CONCLUSION

Based on the aggregator business model, the demand aggregator has the dual role of the electricity industry and the execution DR agent. This study focuses on the use of DR strategy and AS allocation to achieve power suppression from the main grid, peak load suppression, and active DG sources. Thus, increasing the use of DG can increase investors' willingness to expand the capacity of energy storage systems, high-performance energy conversion equipment, small renewable power generation systems, and small-scale power plants. Integrating with the public construction of AMI, more renewable energy operators or manufacturers are willing to invest in the expansion of hardware and software equipments. Under the aggregator business operation model, from the one-way provision of user power service architecture, gradually adjust to the supply and demand sides to share real-time information and two-way mutual sale of power. In addition to the user's own power consumption, the Open Access Same-Time Information System can provide incentives such as time price, instant price, and power outage, to attract users to cluster and appoint an aggregator, and then execute DR transaction bidding to obtain preferential electricity price.

This study has validated the CT and DGM methods, which can be applied to the aggregator business operation model with the demand and generation aggregators. The CT method is employed to estimate the optimal interruptible power capacity such that both the electricity industry and the user group can accept and perform within a smart grid. After the DR, according to the user group's demand, DG available capacity, and risk evaluation, the DG resources can be fairly distributed to the users participating in the cooperative DR strategy using the DGM method. The experimental results show that the DR and AS allocation can be implemented during the peak periods, and he average power consumption of the peak periods can be educed about 20.91% within 8 timing slots.

After implementation, the user group gets the electricity cost deduction and can reduce the power demand from the main grid. In addition to effectively utilizing the power of DG supplies, the bi-direction communication (intero-perability and security) functions of smart grids, such as smart meter devices and VNM networks, should be strengthened to actually grasp the power consumption of the user group and monitor the status of the DG. In addition, government policies are required to encourage the construction of regional power pools at the customer end, such as a small decentralized power generation, energy storage systems, solar photovoltaic system, and electricity cogeneration, for example, the installation of roof-type agricultural-land, and stagnation-pond solar photovoltaic systems, which can increase renewable energy capacity, thereby relieving the risk of unstable renewable energy. Under this business operation model structure, it is expected that the electricity industry and the user group will achieve a win-win situation.

APPENDIX

The procedure of DR and DG distribution is shown in Figure 8. Based on 1-h-ahead strategy, one day can be divided into 8 timing slots. During the contract timing slot, including peak period (10:00 a.m.- 12:00 a.m. and

13:00 p.m.–17:00 p.m.) and partial peak period (12:00 p.m.–13:00 p.m), each DR aggregator can perform the DR schedule via 1-h-ahead strategy and announce the electricity price, customers' electricity demands, DG demand, and available DG capacity. Using the proposed CT and DGM methods, the DR schedule can be achieved with the estimated interruptible power capacity, and then the DG distribution can be determined in the contractual timing slot by the DGM method.

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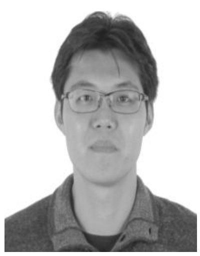

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